Spin Manipulation with an RF Wien-Filter at COSY

PSTP Workshop 2015

Bochum, September 15, 2015 | Sebastian Mey and Ralf Gebel for the JEDI Collaboration |

Forschungszentrum Jülich

Content

Motivation

JEDI Collaboration: First direct measurement of charged light hadrons' permanent **E**lectric **D**ipole **M**oment in storage rings

- simple system with EDM $\vec{d}$ and MDM $\vec{\mu}$ aligned with spin $\vec{S}$

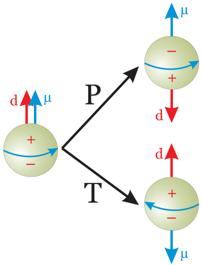
$$\mathcal{H} = -\mu\frac{\vec{S}}{S}\cdot\vec{B} - d\frac{\vec{S}}{S}\cdot\vec{E}$$

$$\mathcal{P}(\mathcal{H}) = -\mu\frac{\vec{S}}{S}\cdot\vec{B} + d\frac{\vec{S}}{S}\cdot\vec{E}$$

$$\mathcal{T}(\mathcal{H}) = -\mu\frac{\vec{S}}{S}\cdot\vec{B} + d\frac{\vec{S}}{S}\cdot\vec{E}$$

$\Rightarrow$ EDMs violate tests **both** parity $\mathcal{P}$ and time reversal $\mathcal{T}$ symmetry

- CPT Theorem: permanent EDMs violate $\mathcal{CP}$ symmetry



source: en.wikipedia.org

Spin Motion in a Magnetic Storage Ring

JEDI Collaboration: First direct measurement of charged light hadrons' permanent EDM in storage rings

- spin motion: $\frac{\mathrm{d}\vec{S}}{\mathrm{d}t} = \vec{S} \times (\vec{\Omega}_{\mathrm{MDM}} + \vec{\Omega}_{\mathrm{EDM}})$ (Thomas-BMT Equation)

$$\vec{\Omega}_{\mathrm{MDM}} = \frac{q}{m}\left((1+\gamma G)\vec{B}_{\perp} + (1+G)\vec{B}_{\parallel} - \left(\frac{\gamma}{\gamma+1} + \gamma G\right)\vec{\beta} \times \vec{E}/c\right)$$

$$\vec{\Omega}_{\mathrm{EDM}} = \frac{q}{m}\frac{\eta}{2}\left(\vec{E}/c + \vec{\beta} \times \vec{B}\right)$$

- MDM: $\vec{\mu} = 2(G+1)\frac{q\hbar}{2m}\vec{S}$ with anomalous magnetic moment G
- EDM: $\vec{d} = \eta\frac{q\hbar}{2mc}\vec{S} \approx 10^{-31}$ ecm $\Leftrightarrow$ $\eta \approx 10^{-15}$ for SM light hadrons

Spin Motion in a Magnetic Storage Ring

JEDI Collaboration: First direct measurement of charged light hadrons' permanent EDM in storage rings

- spin motion: $\frac{d\vec{S}}{dt} = \vec{S} \times (\vec{\Omega}_{\text{MDM}} + \vec{\Omega}_{\text{EDM}})$ (Thomas-BMT Equation)
- stationary ring with vertical guiding field $\vec{B}_\perp$ and $\vec{B}_\parallel = \vec{E} = \vec{0}$

$$\vec{\Omega}_{\text{MDM}} = \frac{q}{m}\left((1+\gamma G)\vec{B}_\perp + (1+G)\vec{B}_\parallel - \left(\frac{\gamma}{\gamma+1} + \gamma G\right)\vec{\beta} \times \vec{E}/c\right)$$

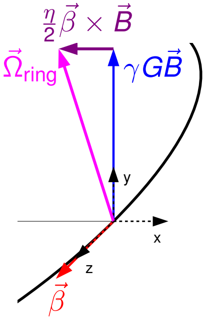
$$\vec{\Omega}_{\text{EDM}} = \frac{q}{m}\frac{\eta}{2}\left(\vec{E}/c + \vec{\beta} \times \vec{B}_\perp\right)$$ couples to motional electric field

- MDM: $\vec{\mu} = 2(G+1)\frac{q\hbar}{2m}\vec{S}$ with anomalous magnetic moment G
- EDM: $\vec{d} = \eta\frac{q\hbar}{2mc}\vec{S} \approx 10^{-31}$ ecm $\Leftrightarrow$ $\eta \approx 10^{-15}$ for SM light hadrons

Generating an EDM Signal

stationary ring with vertical guiding field $\vec{B}$ and $\vec{B}_{\|} = \vec{E} = \vec{0}$

$$\vec{\Omega}_{\text{ring}} = \frac{q}{m}\left((1+\gamma G)\vec{B} + \frac{\eta}{2}\vec{\beta}\times\vec{B}\right)$$



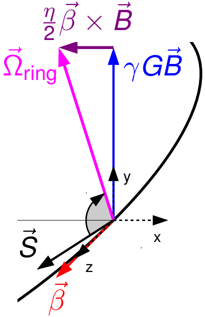
- spin precession around vertical axis with tune γG
- tiny EDM tilt of precession axis
- prepare beam with purely horizontal spins

$\Rightarrow$ oscillating vertical spin component, but signal mutch too small to observe

Generating an EDM Signal

stationary ring with vertical guiding field $\vec{B}$ and $\vec{B}_{\parallel} = \vec{E} = \vec{0}$

$$\vec{\Omega}_{\text{ring}} = \frac{q}{m}\left((1+\gamma G)\vec{B} + \frac{\eta}{2}\vec{\beta}\times\vec{B}\right)$$



- spin precession around vertical axis with tune γG
- tiny EDM tilt of precession axis
- prepare beam with purely horizontal spins

$\Rightarrow$ oscillating vertical spin component

- introduce additional in-plane spin kick in phase with precession

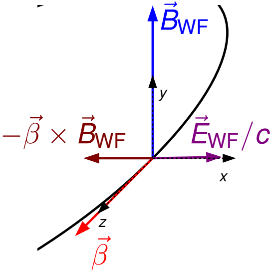
$\Rightarrow$ oscillating spins point forward most of the time

$\Rightarrow$ **continuous build-up of vertical spin component $\Rightarrow$ EDM Signal**

Generating an EDM Signal, cont.

- supplement lattice with **local** vertical magnetic field $\vec{B}_{\mathrm{WF}}$ oscillating with spin precession
- minimize beam perturbation by adjusting net Lorentz Force to zero

$$\vec{E}_{\mathrm{WF}}/c = -\vec{\beta} \times \vec{B}_{\mathrm{WF}} \text{ (Wien-Filter condition)}$$



  - additional spin rotation in RF Wien-Filter around vertical axis

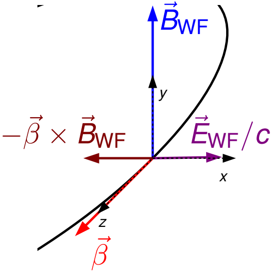
$$\vec{\Omega}_{\mathrm{MDM}} = \frac{q}{m}\left((1+\gamma G)\vec{B}_{\mathrm{WF}} - \left(\frac{\gamma}{\gamma+1} + \gamma G\right)\vec{\beta} \times \vec{E}_{\mathrm{WF}}/c\right)$$

$$\vec{\Omega}_{\mathrm{EDM}} = \frac{q}{m}\frac{\eta}{2}\left(\vec{E}_{\mathrm{WF}}/c + \vec{\beta} \times \vec{B}_{\mathrm{WF}}\right) = \vec{0}$$

Generating an EDM Signal, cont.

- supplement lattice with **local** vertical magnetic field $\vec{B}_{\mathrm{WF}}$ oscillating with spin precession
- minimize beam perturbation by adjusting net Lorentz Force to zero

$\vec{E}_{\mathrm{WF}}/c = -\vec{\beta} \times \vec{B}_{\mathrm{WF}}$ (Wien-Filter condition)



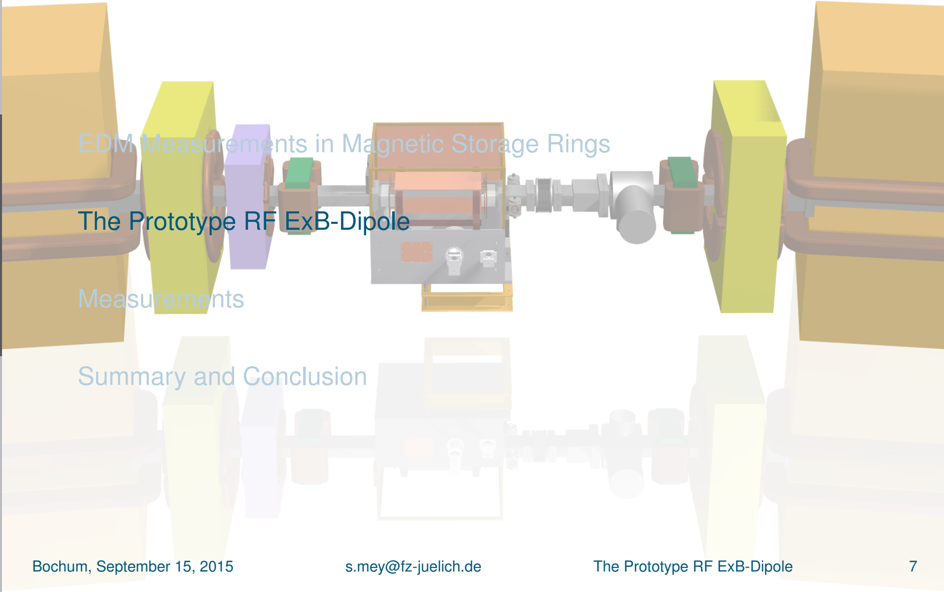
- additional spin rotation in RF Wien-Filter around vertical axis

$$\vec{\Omega}_{\mathrm{MDM}} = \; = \frac{q}{m}\frac{1+G}{\gamma}\,\vec{B}_{\mathrm{WF}}$$

The RF Wien-Fielter itself is EDM transparent, but is capable of generating an EDM signal due to modulation of the spin precession.*

[* W. M. Morse, Y. F. Orlov and Y. K. Semertzidis, Phys. Rev. ST Accel. Beams 16, 114001 (2013)]

Content



- EDM Measurements in Magnetic Storage Rings
- The Prototype RF ExB-Dipole
- Measurements
- Summary and Conclusion

Prototype RF Wien-Filter with Radial Magnetic Field

$-\vec{\beta} \times \vec{E}/c$

x $\vec{B}$

z $\vec{E}/c$

$\vec{\beta}$ y

- investigate action of RF Wien-Filter fields by direct observation of resulting MDM motion

$\Rightarrow$ use radial magnetic field with vertically prepared spins

$\Rightarrow$ continuous rotation of spin vector during operation

- Lorentz force compensation: $\vec{E}/c = -\vec{\beta} \times \vec{B}$
- spin precession: $\vec{\Omega}_{\text{MDM}} = \frac{1+G}{\gamma}\vec{B}$
- particles sample localized RF field once each turn at orbit angle θ

$$\Rightarrow \quad b(\theta) = \int \hat{B}\,\mathrm{d}z \cos\left(\frac{f_{\text{RF}}}{f_{\text{rev}}}\theta + \phi\right) \sum_{n=-\infty}^{\infty} \delta(\theta - 2\pi n)$$

Resonance Strength of an RF Wien-Filter

- intrinsic resonance strength given by spin rotation per turn, calculate Fourier integral over driving fields along orbit*:

$$
\begin{aligned}
\epsilon_K = \frac{f_\text{spin}}{f_\text{rev}} &= \frac{1+G}{2\pi\gamma} \oint \frac{b(\theta)}{B\rho} e^{iK\theta}\, \mathrm{d}\theta \\
&= \frac{1+G}{2\pi\gamma} \frac{\int \hat{B}\, \mathrm{d}z}{B\rho} \sum_{n=-\infty}^{\infty} \cos\left(2\pi n \frac{f_\text{RF}}{f_\text{rev}} + \phi\right) e^{i2\pi K n} \\
&= \frac{1+G}{2\cdot 2\pi\gamma} \frac{\int \hat{B}\, \mathrm{d}z}{B\rho} \sum_n e^{\pm i\phi} \delta\left(n - K \mp \frac{f_\text{RF}}{f_\text{rev}}\right)
\end{aligned}
$$

- spin tune $\approx \gamma G$, resonance at every sideband with
  $K \stackrel{!}{=} \gamma G = n \pm \frac{f_\text{RF}}{f_\text{rev}} \;\Leftrightarrow\; f_\text{RF} = f_\text{rev} |n - \gamma G|;\; n \in \mathbb{Z}$
- d at 970 MeV/c: $f_\text{rev} = 750.603\,\text{kHz}$; $\gamma G = -0.16098$

n	0	1	-1	2	-2
f_{RF}/ kHz	120	629	871	1380	1621

[* S. Y. Lee, 10.1103/PhysRevSTAB.9.074001 (2006)]

The Prototype RF ExB Dipole

coil: 8 windings
length 560 mm

distance 54 mm
length 580 mm

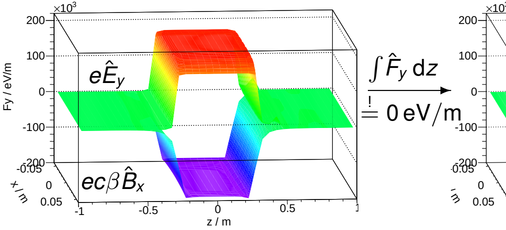
Parameters	**RF B dipole**
P_{RMS} / W	90
$\hat{I}$ / A	5
$\int \hat{B}_x \, \mathrm{d}l$ / Tmm	0.175
f_{RF} range / kHz	629 - 1170

The Prototype RF ExB Dipole

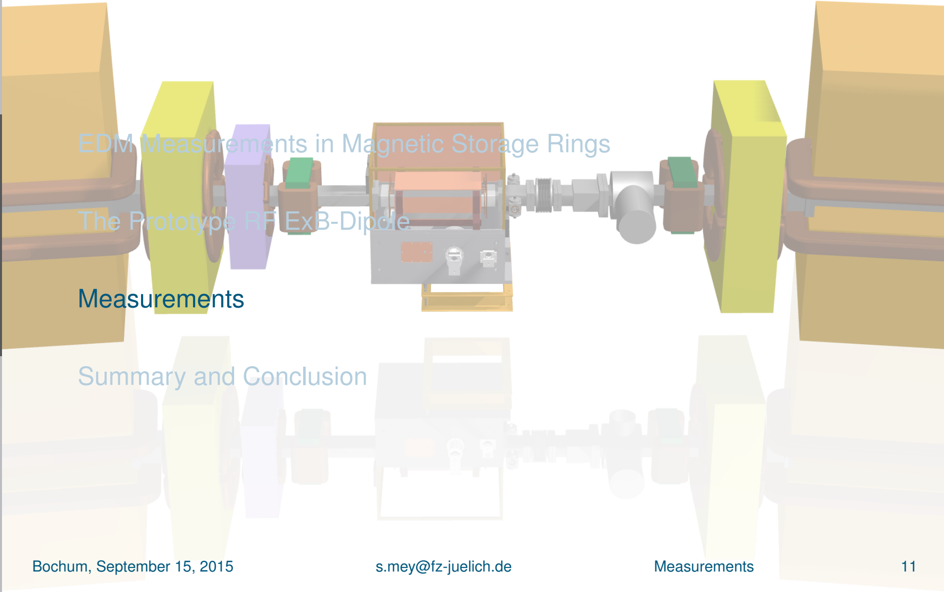
coil: 8 windings

distance 54 mm

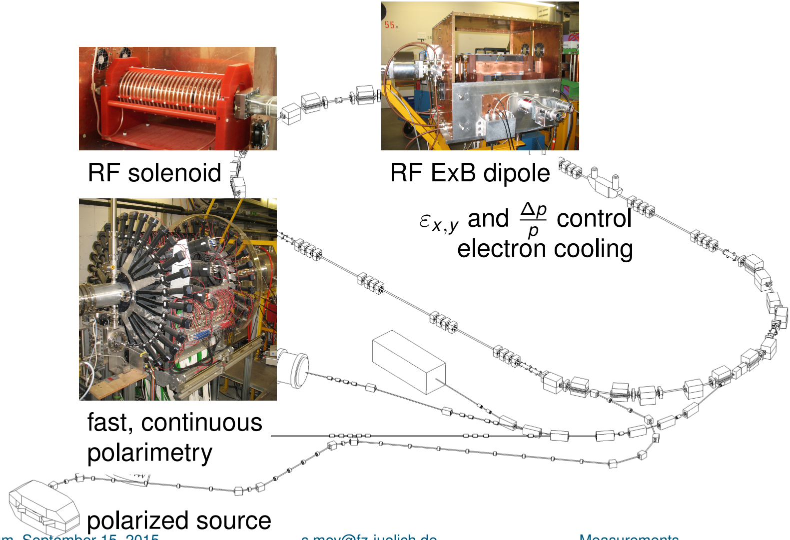
length 580 mm



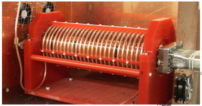
Content



COSY as Spin Physics R&D Facility



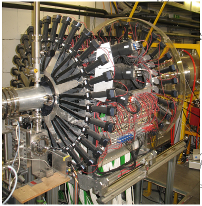
COSY as Spin Physics R&D Facility



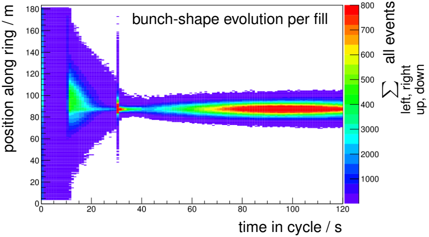
RF solenoid

RF ExB dipole

$\varepsilon_{x,y}$ and $\frac{\Delta p}{p}$ control
electron cooling



fast, continuous
polarimetry



polarized source

RF ExB Setup for Field Compensation

- move betatron sideband onto RF freq. for max. sensitivity

$$q_y \cdot f_{\text{rev}} \stackrel{!}{=} (1+\gamma G) f_{\text{rev}} = 629\,\text{kHz}$$

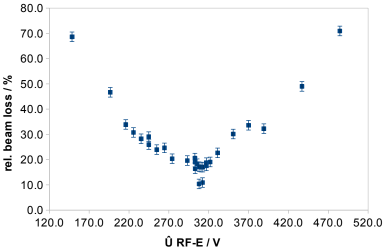
- polarimeter target directly above beam limits acceptance

$\Rightarrow$ exited part of beam is removed

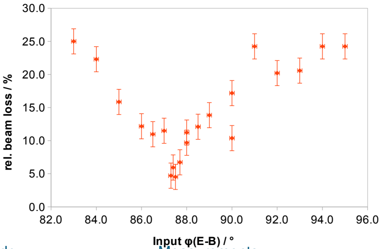
$\Rightarrow$ diagnosis with COSY beam current transformer over $\Delta t = 30\,\text{s}$

- determination of amplitudes and phase corresponding to Lorentz force compensation down to per mille!

Amplitude Scan RF-E at $\hat{I}_{\text{RF-B}} = 2\,\text{A}$



Phase Scan



Beam Response

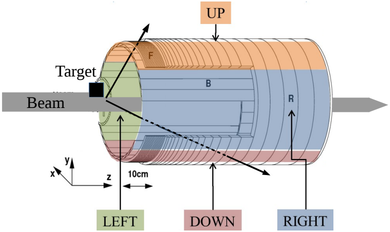
Analogue signal from one vertical BPM pickup electrode during RF operation exactly **on resonance**
Center $f_{qy} = f_{\text{rev}}(1 + q_y) = 1380\,\text{kHz}$, Span $\Delta f = 10\,\text{kHz}$

RF Wien-Filter:
$\hat{I}_{\text{RF-B}} \approx 740\,\text{mA}$; $\hat{U}_{\text{RF-E}} \approx 108\,\text{V}$

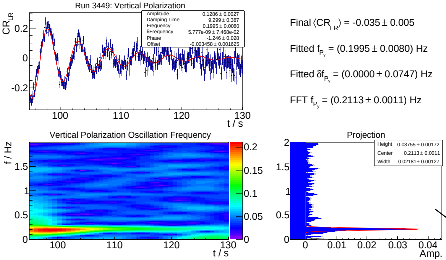
RF Sol.:
$\hat{I}_{\text{Sol.}} \approx 780\,\text{mApp}$

Polarization Measurements

- beam polarization $\Leftrightarrow$ average over all particles' spins
- massive carbon target with slow extraction $\Rightarrow$ long observation time
- polarization signal $\Rightarrow$ rate asymmetries in $^{12}\mathrm{C}(\vec{\mathrm{d}},\mathrm{d})$: $P_y \propto \frac{N_{\mathrm{left}} - N_{\mathrm{right}}}{N_{\mathrm{left}} + N_{\mathrm{right}}}$
- continuous rotation of $\vec{P}$ $\Rightarrow$ oscillation of P_y

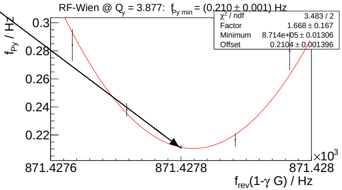


Measurement Resonance Strength



- RF Wien-Filter and RF Solenoid both drive continuous rotation of $\vec{P}$
- find resonance by scan of driving frequency

$$f_{\mathrm{RF}} \stackrel{!}{=} f_{\mathrm{rev}}(1-\gamma G)$$



- total spin flip only on resonance ⇒ average polarization → 0

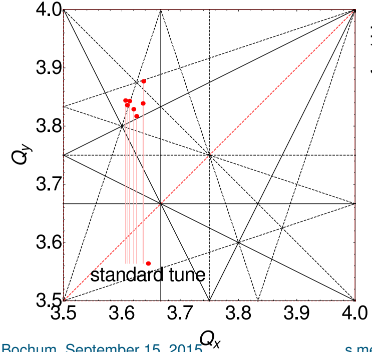
⇒ minimum of oscillation frequency f_{Py}

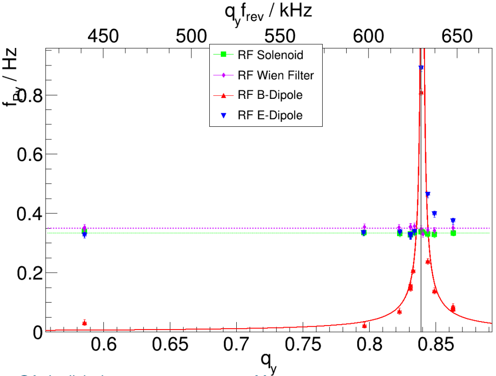
- measurement of resonance strength

$$\varepsilon = \frac{f_{Py\,\mathrm{min}}}{f_{\mathrm{rev}}}$$

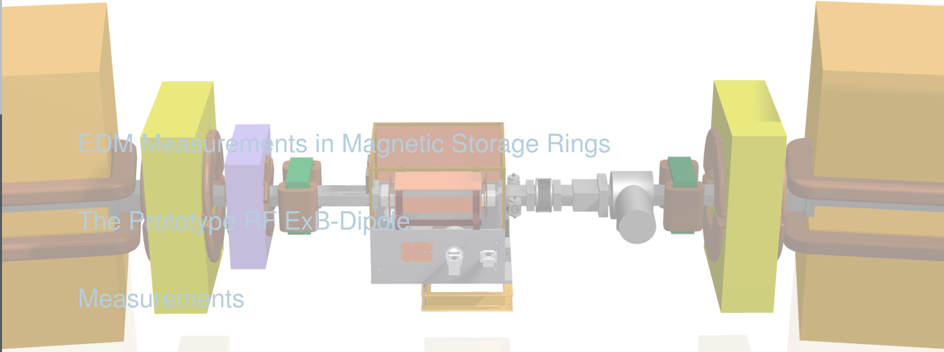
Preliminary result of Fixed Frequency Scans

- resonance strength measurements to determine level of field compensation
- RF Solenoid: $f_{P_y} = \frac{q}{p}\frac{1+G}{4\pi}\int \hat{B} \mathrm{d}\, l$ RF Wien-Filter: $f_{P_y} = \frac{q}{p}\frac{1+G}{4\pi\gamma}\int \hat{B} \mathrm{d}\, l$
- RF B-Dipole: $f_{P_y} = \frac{q}{p}\frac{1+\gamma G}{4\pi}\int \hat{B} \mathrm{d}\, l +$ interference due to beam motion
- RF E-Dipole: $f_{P_y} = \frac{q}{mc^2}\frac{1/\gamma+1+G}{4\pi}\int \hat{E} \mathrm{d}\, l +$ interference due to beam motion





Content



EDM Measurements in Magnetic Storage Rings

The Prototype RF ExB-Dipole

Measurements

Summary and Conclusion

Summary

- versatile prototype RF ExB dipole with minimal excitation of coherent beam oscillations has been successfully commissioned
- $P_{\mathrm{RMS}} = 90\,\mathrm{W} \Rightarrow \int \hat{B}_x\,\mathrm{d}l = 0.175\,\mathrm{T\,mm};\ \int \hat{E}_y\,\mathrm{d}l = 24.1\,\mathrm{kV}$

  Frequency Range 630 kHz - 1060 kHz
- entirely beam-based method for field matching has been worked out and verified
- spin manipulation performance on the same level as with the "proven" RF-Solenoid"system

Outlook

- first attempt of a direct measurement of the deuteron EDM requires a upright, high precision version of an RF Wien-Filter
- rotatable stripline solution scheduled for commissioning at COSY in summer 2016

$\Rightarrow$ introduction of the concept and field simulations $\rightarrow$ J. Slim, “Towards a High-Accuracy RF Wien Filter for Spin Manipulation at COSY Jülich”

Content